The Use of Position-Tracking Drifters in Riverine Environments

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***Abstract*-Small, inexpensive GPS-equipped drifters are described for use in natural rivers and streams. The Lagrangian drifters allow for near-continuous position observations providing estimates of the mean flow field, pathways, and dispersion in natural riverine environments. A discussion of limitations and statistical methods is provided. Twenty river drifters were released in clusters in three different reaches on the Skagit River, WA, USA. The results highlight the ease of use and the broad range of information river drifters afford scientists and engineers.**

I. INTRODUCTION

Position tracking drifters offer a new perspective in describing flow characteristics in riverine environments that have been overlooked in previous studies. To date, most riverine observations are based on fixed Eulerian observations, which have limitations in completely describing material transport. Mean flow field and dispersion estimates are typically the two most common observations obtained with Eulerian observations in riverine environments. Due to cost and logistical constraints Eulerian observations are limited to a small number of fixed measurements reducing their spatial description. Acoustic Doppler Current Profilers (ADCPs) have increased flow observations into the vertical and generally across a channel, improving discharge estimates. ADCPs can be used to spatially map the flow field over larger distances. However, Eulerian observations can not accurately describe the particle pathways and assumptions must be made concerning river kinematics between observations points.

For estimating dispersion, river field studies have used radioactive or fluorescent tracers by recording concentrations at fixed locations downstream of an injection point [1-9]. A number of theoretical and empirical dispersion models were developed from these types of observations [10-12]. Deploying additional tracer concentration sensors is cost prohibitive, therefore cross-channel (transverse) mixing and vertical estimates are often inferred or limited. In most rivers, the ratio of width to depth is large causing the tracer to rapidly mix in the vertical before becoming mixed in the transverse. In order to predict the far field longitudinal dispersion, assuming that vertical mixing is short, an accurate estimate of transverse mixing is still required. When the tracer is completely mixed in the vertical and transverse dimensions, the three dimensional advection dispersion equation can be simplified to one-dimension.

The use of Global Positioning System (GPS)-equipped drifters provides high temporal and spatial resolution data unattainable by tracer concentration methods or Eulerian velocity observations. The riverine community has typically not used drifters in their studies. Previous drifters required direct line of sight making it difficult to track their positions with accuracy over long distances, which are required for dispersion estimates [13,14]. Tracer studies were advantageous in this respect. Recent advances in GPS technology have decreased the cost and size of GPS handheld units, while position accuracy has increased. It is now possible to build a large number of inexpensive (~$300), small GPS-equipped drifters for O(km)-O(hrs) applications, such as riverine environments [15]. GPS-equipped drifters allow for a near-continuous observation of their relative expansion and a better estimate of advection and mixing in both the transverse and longitudinal directions as a function of time and space. Lagrangian drifter observations provide information of the particle pathways and material transport for sediment, biotic, abiotic and pollutants. Moreover, drifter position data can be spatially averaged to obtain a gridded velocity flow field.

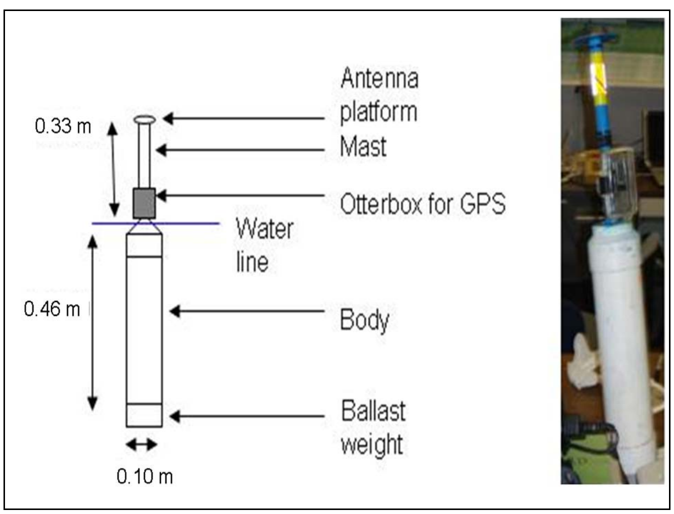

Fig. 1 Schematic of the GPS-equipped river drifter and photograph.

Twenty river drifters were released on the Skagit River, WA, and neighboring marsh channels in later September, 2008. The use of GPS-equipped drifters in a riverine environment and associated statistical methods, cost estimates, and results are described below.

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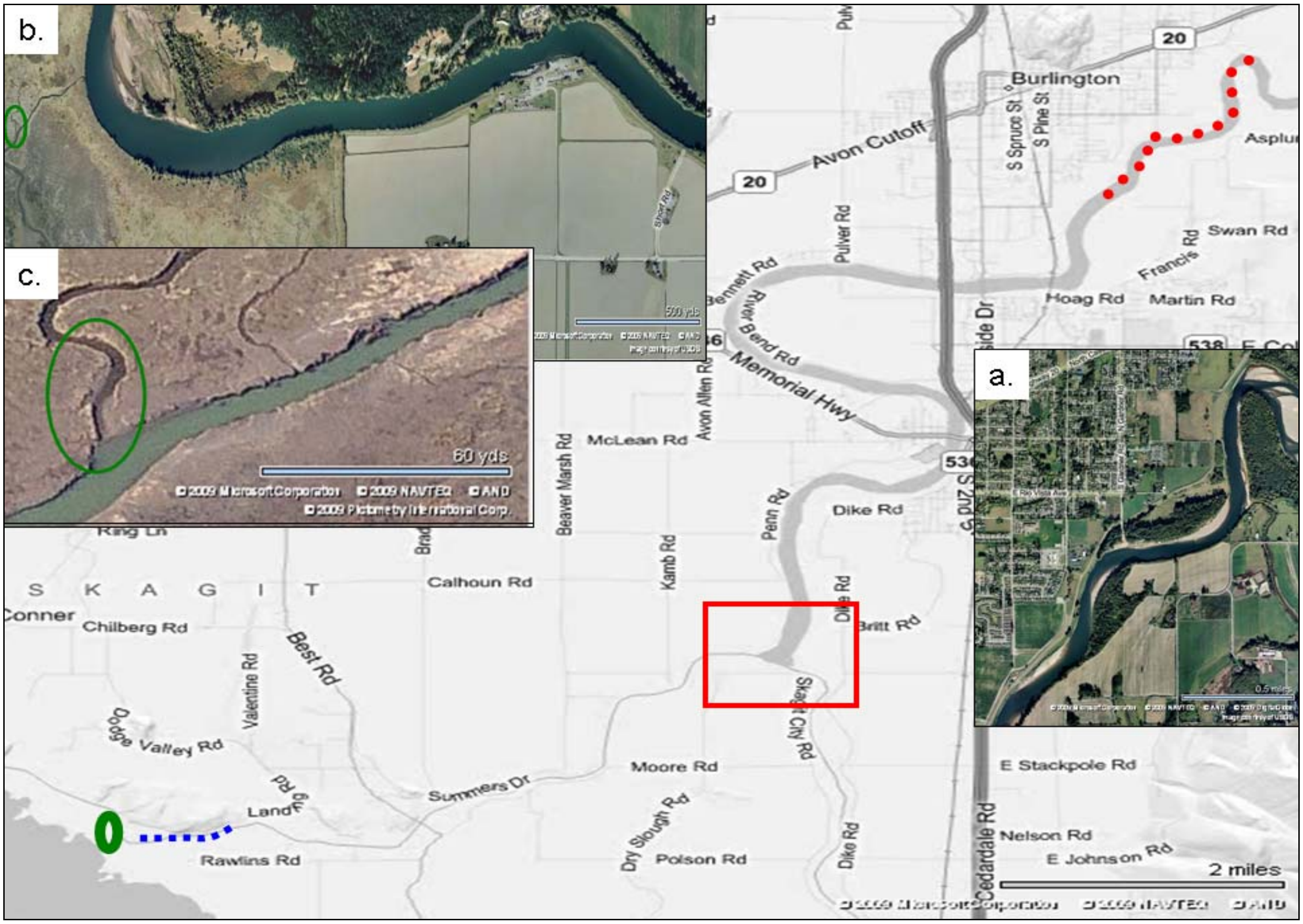

Fig. 2 Vicinity map of the Skagit River, WA, U.S.A. and drifter deployment reaches: (a) Upper Skagit, red dotted line, (b) North Fork, blue dotted line and (c) Marsh Channel, green oval. The Skagit River flows from the northeast corner of the figure to the southwest, splitting into the North and South forks (red square) before flowing into Skagit Bay. Scales of insets are shown in the bottom right corner of each inset.

II. River Deployment and processing

A. River Drifter

Reference [16] demonstrated the feasibility of mounting a handheld GPS receiver onto an inexpensive PVC float to describe flow behavior within the surf zone. The handheld GPS was the size and weight of a cell phone and had internal logging and power capabilities. The GPS internal memory supports 5400 positions, in post-processing mode, can sample at intervals ranging from 2 to 240 seconds and allows for 8 hours of continuous sampling. The GPS absolute position and speed errors are 0.4 m and 0.01 m s^{-1}. Survey-grade post-processing software is also required to achieve the stated position accuracies, which costs ~$2000.

For this type of GPS, the largest source of positioning error is related to signal multi-pathing associated with their inexpensive patch antennas [17]. To reduce multi-pathing, the GPS patch antenna was placed on a 0.07 m diameter circle of aluminum sheeting. This reduced the position errors by an order of magnitude. In a wavy surfzone environment, the GPS-equipped drifters closely followed a simultaneously released patch of dye, verifying that the drifter observations are valid Lagrangian tracer estimates [16]. The same GPS receiver is used for the river drifter.

The river drifter body is also a modification of the surfzone drifter [16]. The river drifter consists of a ballasted, subaqueous 0.46 m long by 0.10 m diameter PVC central tube connected to a 0.33 m long antenna mast of 0.03 m diameter PVC (Fig 1). The drifters are ballasted with a low center of gravity to reduce potential pitch and roll effects. The handheld GPS is housed in a waterproof plastic box attached to the drifter near the waterline. The compact design of the drifter allows for a number of drifters

to easily be transported to the field site, placed on a vessel, or manually carried to shallow streams. The complete drifter weighs only 3.6 kg and costs ~$300. Note that twenty drifters cost ~$6,000, which is approximately the same cost of one tracer-dye concentration sensor, or one-fourth the cost of an ADCP.

B. Drifter Deployment Overview

Seven drifter deployments were performed between September 25th through 27th 2008 for three different reaches (Upper Skagit, North Fork and Marsh Channel) of the Skagit River (Fig 2). The flow speed, reach length, and channel width varied between each reach (Table 1). Two different deployment schemes were used. The first deployment scheme, drifters were simultaneously released near the center of the channel in a large group, referred to as a cluster. For the second deployment scheme drifters were released across the channel at relatively constant separation interval, referred to as line abreast.

TABLE 1:

REACH SUMMARY

Location	Upper Skagit	North Fork Skagit	Marsh
# of Drifters Used	14	16	6
Drift Time [s]	3600	2400	200
Average Flow Speed [ms^{-1}]	1.10	0.55	0.16
Reach Length [m]	3500	1400	35
Channel Width [m]	125-158	93-154	2

The Skagit River originates in southwestern British Columbia, Canada and flows Southeasterly through Washington, U.S.A before draining into the Puget Sound. The Upper Skagit River is composed of a sinuous channel containing 3 to 4 bends in alternating directions, and varying in width from 125 to 158 m (Fig 2a). The mean river speed was 1.10 ms^{-1}. The river divides approximately 14 km downstream. The northern branch of the divide is known as the Northfork Skagit River. The Northfork is weakly sinuous with slightly narrower, 93-154 m, channel (Fig 2b). The mean river speed on the Northfork was 0.55 ms^{-1}, half the speed of the Upper Skagit flow. Lastly, a short deployment was made in a small, 2 m wide, sinuous marsh channel which contained one complete meander (Fig 2c). At the time of deployment, the measured mean speed of the channel was 0.16 ms^{-1}.

The Upper Skagit and Northfork drifter releases were conducted from a small boat. The marsh channel release point was inaccessible by boat and the drifters were carried to the deployment location. Two people carried eight drifters through the marsh and hand-released them from the channel bank 40 m upstream. The deployment was conducted during an ebbing tide in an effort to capture the strongest current in this small channel.

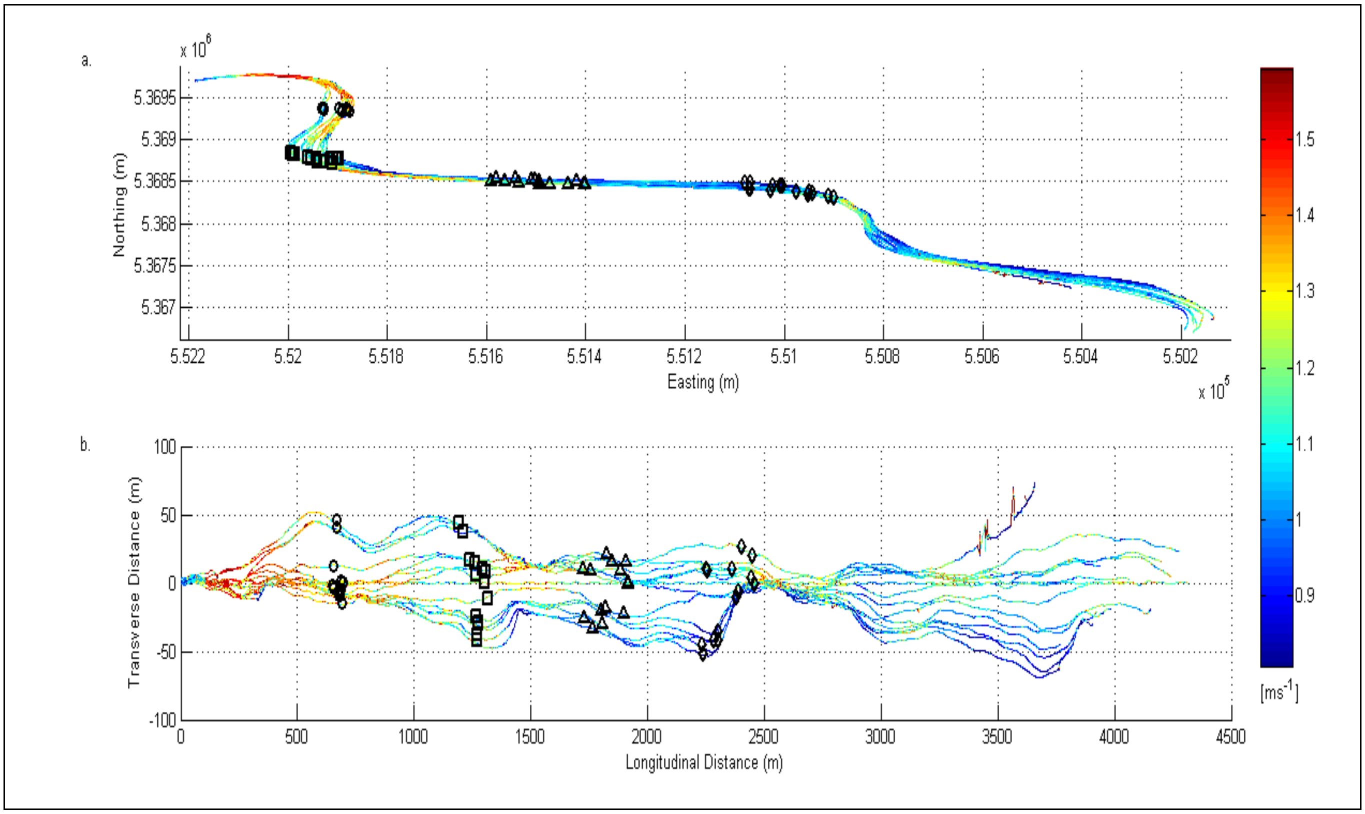

Fig. 3: Upper Skagit deployment coordinate transform: (a) geographic coordinates, (b) river-fitted local coordinate frame utilizing Legleiter and Kyriadkidis (2007) technique. Symbols represent the position of the drifters at 500 (circle), 1000 (square), 1500 ((triangle) and 2000 (diamond) seconds after release. Colorbar plotted on the right, where color represents drifter speed.

C. Quality Control and River Coordinate Frame Transform

The time series of drifter positions were quality-controlled by removing erroneous points that exceeded three velocity standard deviations. Time gaps in the data were interpolated with a spline algorithm for gaps less than 10 seconds and a linear algorithm for gaps greater than 10 seconds. A 62 second moving average was applied to smooth the river data and a 5 second moving average was applied to the marsh channel. Velocity estimates were computed using a forward-differencing scheme.

A few drifters were snagged on riverbank obstructions such as: trees, logs, boat docks, and rocks. Due to a limited number of drifters, one snagged drifter can cause rapid unnatural growth in the dispersion. To address this problem, the data from snagged drifters were removed by visual inspection.

A geographic coordinate frame is not ideal for describing the statistical behavior of the flow, owing to the sinuosity of the channels. Therefore the geographic coordinate system was transformed to a local orthogonal curvilinear coordinate system, where the longitudinal axis (s) is along the river centerline, and the transverse axis (n) is normal to the river centerline. Legleiter and Kyriadkidis [18] generously provided the MATLAB code to transform the coordinate frame of each deployment reach to a local river coordinate frame (s,n). The accuracy and precision of the coordinate transform is primarily a function of curvature and discretization of the centerline. Errors associated with the transformation are O(cm) [18]. Additional quality controls, as described above, were performed to remove erroneous points after the transformation. An example of the transformation is shown in Fig (3) for the Upper Skagit reach, where 14 individual drifter tracks and speeds are plotted in geographic (Fig 3a) and local coordinates (Fig 3b). The speeds compare well between each coordinate frame. In the local coordinate frame, the magnitude of the transverse drifter convergence and divergence is clearly seen, but the geographic coordinate frame is required to show flow fluctuations associated with river meanders. The cluster's separation is controlled by the river meanders, ranging from 3 m to 100 m. The drifter's relative distribution in time is illustrated by the symbols showing the drifter positions 500, 1000, 1500 and 2000 seconds after release.

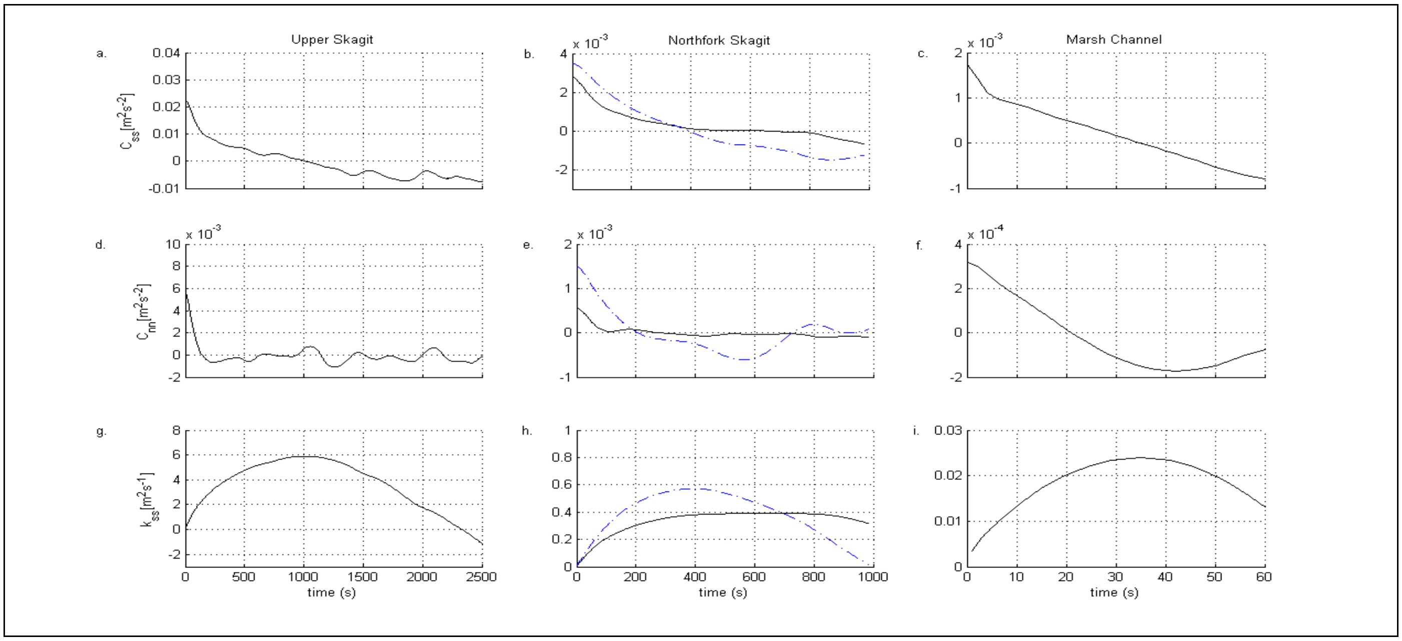

Fig. 4: Autocovariance anomalous velocity functions for the Upper Skagit (left column), Northfork (middle column) cluster release (solid line) and line breast release (dashed line) and Marsh Channel (right column). Longitudinal (C_{ss}) (a-c), transverse (C_{nn}) (d-f) and longitudinal single-particle diffusivities (k_{ss}) (g-i)

III. Drifter Statistics

A. Eulerian Velocity Mapping Calculation

If two drifters are released at the same location, but at different times, or if they are released at slightly different locations at the same time, they will generally follow very different paths associated with coherent and random fluid motions. A measure of the spatial and temporal scales for coherent and random fluid motions is required, such that proper statistical confidence levels describing the uncertainties are obtained [19].

Spatial binning the drifter observations is required to properly describe the Eulerian flow field. However, there is a compromise between the spatial resolution, bin size, and statistical confidence. Five or more independent observations are required within a bin to be statistically significant [20]. The number of independent observations, known as degrees of freedom (DOF), in a bin is determined by the total time that the drifters occupy a bin divided by the Lagrangian decorrelation time, T_L, given by:

$$DOF_{bin} = \frac{\sum_{j=1}^{N} t_i}{T_L} \tag{1}$$

where DOF_{bin} is degrees of freedom for each bin, j denotes each individual drifter and t_i is the time each drifter spent inside an individual bin. T_L represents fluid particle memory and describes the time scale of the longest fluctuation. Therefore, a priori knowledge of this time is required to adequately select the longitudinal and transverse bin dimensions.

T_L is directly calculated from the ensemble average of the autocovariance function, $C_{ii}(\tau)$, for each drifter concurrently deployed, and is defined as:

$$C_{ii}(\tau) = \left\langle v_i^{'}\left(t'=0\right) v_i^{'}\left(t'=\tau\right)\right\rangle \tag{2}$$

where $v^{'}$ is the anomalous drifter velocity which is calculated by removing the ensemble mean velocity from each individual drifter velocity time series, t' is a relative time step which allows displacement calculations for each drifter for all arbitrary starting positions, i denotes the respective local coordinate direction (s, n), and the angle brackets denote averaging over all drifters for each time lag, τ [20]. Autocorrelation is the autocovariance divided by the covariance, $\left\langle v_i^{'2}\right\rangle = \left\langle v_i^{'}(0) v_i^{'}(0)\right\rangle$, which is also known as the intensity of turbulence squared.

The autocovariance magnitude and shape are similar for multiple deployments but vary between reaches (Fig 4a-f). The variance is an order of magnitude larger for the Upper Skagit (0.02 m^2s^{-2} longitudinal, 0.005 m^2s^{-2} transverse) than the Northfork

(~0.004 m^2s^{-2} longitudinal, ~0.001 m^2s^{-2} transverse) and marsh channel (~0.002 m^2s^{-2} longitudinal, ~0.0003 m^2s^{-2} transverse) due to the larger velocities. The Upper Skagit River longitudinal autocovariance, C_{ss}, becomes negatively correlated after 1000 seconds (Fig 4a). In the North Fork deployments, C_{ss} negatively decorrelate after 400 and 800 seconds (Fig 4b). The autocovariance functions do not asymptote to zero, but instead periodicity is observed owing to the velocity fluctuations associated with river shape.

There are four methods to estimate the T_L from the autocovariance function: 1) the integral temporal scale, 2) absolute diffusivity maxima, 3) zero-crossing or 4) e-folding time. The integral temporal scale is computed by integrating the autocorrelation function over all time lags. The integral of the autocovariance function is absolute diffusivity, k_{ss} (discussed below). The asymptotic diffusivity, k^{∞}, divided by the intensity of turbulence squared corresponds to T_L [21]. The zero crossing is the time lag at the first zero crossing. E-folding time is the time required for the autocovariance function to decrease by a factor of 1/*e*.

The integral method tends to be the standard method used in riverine studies. However, this method was considered an unsuitable descriptor of decorrelation time due to quasi-periodic fluctuations in the mean river speeds with river location. These large scale fluctuations are manifested as oscillating negative and positive residual energies in the autocovariance functions. This resulted in varying decorrelation times using the integral method that were considered inappropriate. The absolute diffusivity maxima method is similar to the integral temporal scale, except that the first maxima of absolute diffusivity in the quasi-periodic autocovariance function is considered to be k^{∞}. The zero crossing method was not used because there are cases for which the autocovariance function asymptotes to a value slightly greater than zero for some time before becoming negative, causing T_L to be larger than expected (Fig 4a,b). Owing to the periodic oscillations and the inconsistent shape prior to the zero crossing in autocovariance anomalous velocity functions, the absolute diffusivity maxima and e-folding time methods provided the most consistent T_L estimates. Both estimates compared well with each other, but are 4 to 20 times shorter then traditional mixing theory estimates (Table 2). Without the ability to directly calculate the autocovariance anomalous velocity function past studies have relied on mixing length theory to provide a rough estimate of T_L [14]. The mixing length equation is given by:

$$L_s = \alpha \frac{Ub^2}{K_n} \tag{3}$$

where L_s is the downstream distance needed for complete mixing, *U* is mean river velocity, *b* is river width, K_n is the transverse diffusivity and α is an empirical scaling constant. There are large uncertainties associated with this calculation because α and K_n are not known. T_L is computed by dividing L_s by U. Natural rivers and streams have riffles, pools, bends, side wall roughness which have large contributions to mixing which are not captured in traditional transverse diffusivity calculations. Incorporating all scales of the river flow using high temporal resolution river drifters provides a much shorter decorrelation time.

TABLE 2:

LAGRANGIAN DECORRELATION TIME

Location	Upper Skagit	North Fork Skagit		Marsh
Deployment Scheme	Cluster Release	Cluster Release	Line Abreast Release	Cluster Release
Longitudinal Decorrelation Time [s]	222	134	188	16
Transverse Decorrelation Time [s]	72	58	110	14
Absolute Diffusivity Maxima Decorrelation Time [s]	258	138	162	14
Mixing Time Theory [s]	3266	22222	23529	80

Once T_L is determined, the proper bin size is selected to ensure statistical confidence. Northfork cluster and line abreast release T_L are approximately 2 and 3 minutes respectively (Table 2).

Therefore, 15 minutes (900 seconds) of drifter data with each bin is required to obtain the minimum 5 DOF to be statistically confident. For example, a mean river velocity of 1 ms^{-1} requires 5 drifters to occupy a bin that is 180 m long or 10 drifters to occupy a bin that is 90 m long to have a statistically significant result. This is highly dependent upon the fluctuations in the rivers, number of drifters deployed, and mean river velocity. An evenly distributed release of drifters is believed to provide the best scenario of measuring the transverse flow field, whereas, a cluster release in the center of the channel would provide the highest longitudinal resolution, with the added benefit of allowing relative dispersion estimates (see "Dispersion and Diffusivity" discussion below). However, this is not necessarily the case. Transverse movement and distribution of the drifters is strongly controlled by river meanders. For that reason, despite deploying in the optimal line abreast configuration, uneven transverse coverage would still remain. In the apex of bends the drifters tend to converge to the outer edge of the channel, limiting the transverse coverage, such as was observed during the line abreast release in the Northfork (Fig 5b,d). Longitudinal bin size of 250 m was needed to attain four to five transverse bins, spanning ~60 m, with greater than 5 DOF. In contrast, the cluster release (Fig 5a,c) had two transverse bins, separated by the centerline, using a finer longitudinal bin of 70 m. Although the cluster release provides large DOF for each bin (as high as 13), the transverse resolution could not be increased. In the line abreast case,

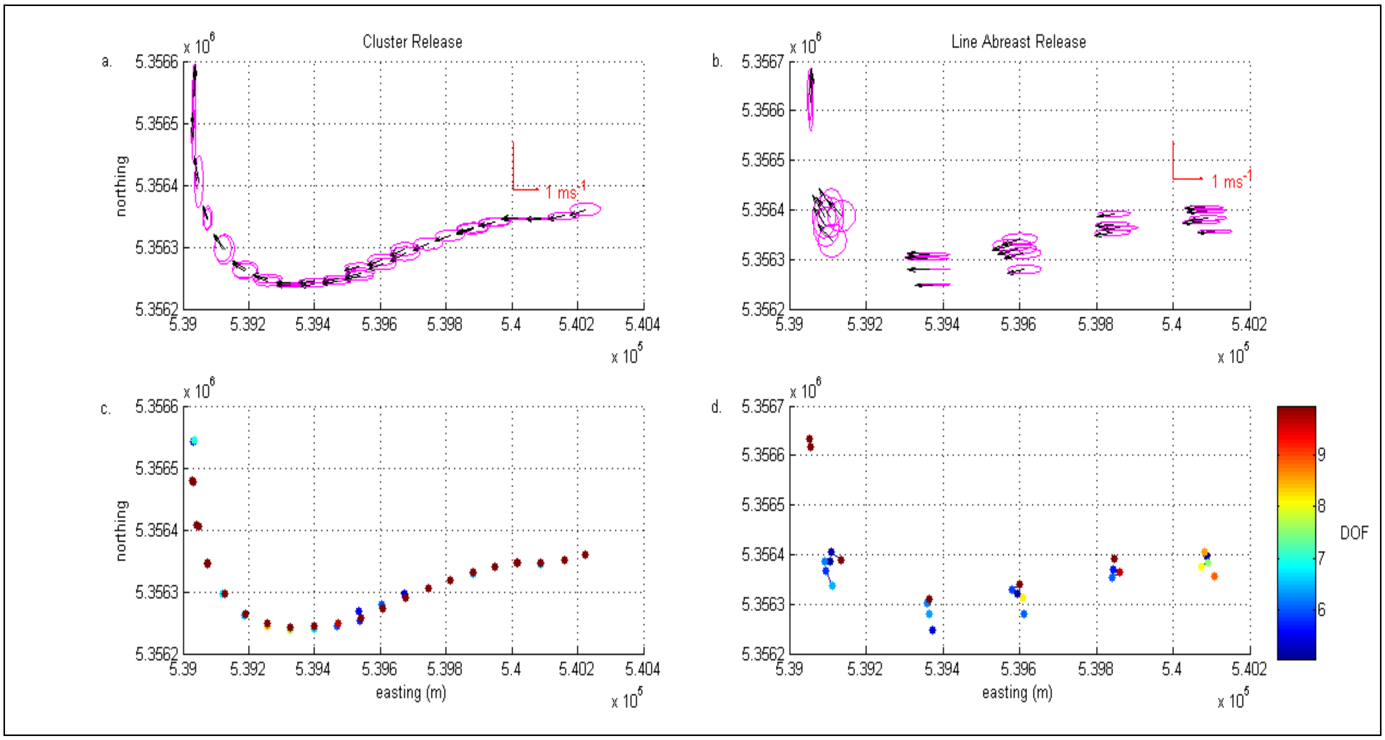

Fig. 5: Plan view of spatially-binned mean velocities and fluctuation ellipses (a,b) for Northfork cluster (left) and line abreast releases (right) . The DOF in each bin are plotted in color with scale to the right (c,d); only bins with greater than 5 DOF are shown. The red vector (a,b) provides a speed scale.

increasing the longitudinal resolution did not ensure transverse coverage throughout the deployment. Once the drifters converged into the sweeping bend the mean speed calculations ultimately became confined to only the outer bin (Fig 5d).

B. Dispersion and Diffusivity

The movement and spreading of a tracer cloud can be quantified by a group of drifters. The ensemble average centroid position of the drifter group provides the overall advection. Spreading about the centroid position in time is measured by the variance, or "relative dispersion". The rate of spreading in time is known as the relative diffusivity, K_i, where i is the respective river frame coordinate direction (s, n). The values of K_s are calculated from the slope of a regression line in the later stages of the deployment, when t $>T_L$, and the values of K_n are calculated as the average slope of increasing dispersion (divergence) and decreasing dispersion (convergence) (Table 3). Fig 6 shows the time evolution of the longitudinal variance of the drifter's positions for the releases on Upper Skagit (a,d), Northfork (b,e) and Marsh Channel (c,f).

Two longitudinal dispersion (Fig 6a,b) regimes are identified in two larger reaches for the cluster deployments. An early stage, when the drifters are in close proximity, and a later stage after the drifter cluster has spread enough to sample the velocity shear in the transverse river profile. In the early stage, the proximity of the drifters suggests they are not experiencing significant velocity shear differences and the spreading is slow. The later stage begins when the drifters have separated enough to experience the transverse profile velocity shear. In this stage, dispersion noticeably increases. The transition from the early to the later regime are seen as a sharp increases in variance. At the transition, the diffusivity values increase from small values, <1.0 m^2s^{-1}, to values >2.0 m^2s^{-1} (Table 3). Note the line abreast deployment (Fig 6b dashed line) exhibits no slow growth stage because immediately upon release the drifter cloud is experiencing large transverse velocity shear.

Another method to estimate spreading and mixing characteristics of a river is from the single-particle statistic. Single-particle statistics consider the ensemble average pathway of a single drifter over many independent releases originating from a common release location. Over many observations a probability density function (PDF) can be created to map the original release position to the probability the drifter will arrive at a position at a later time. The variance is the second moment of the PDF, known as "absolute dispersion". Absolute dispersion estimates differ from the relative dispersion estimates in that both the spread about the center of mass and the advection from the starting position are considered. Absolute diffusivity, k, is calculated as the rate of change of absolute dispersion in time. At long time periods, t >> T_L, relative diffusivity, K, and absolute diffusivity, k, are comparable [20].

TABLE 3:

LONGITUDINAL AND TRANSVERSE DISPERSION COEFFCIENT ESTIMATES

Location		Upper Skagit	North Fork Skagit		Marsh
Deployment		Cluster Release	Cluster Release	Line Abreast Release	Cluster Release
Longitudinal Single Particle Diffusivity [m^2s^{-1}] [k_{ss}]		5.90	0.39	0.57	0.02
Longitudinal Diffusivity [m^2s^{-1}] [K_s]		10.0	0.18	1.47	0.22
Transverse Diffusivity [m^2s^{-1}] [K_n]	Divergent	1.20	0.09	0.85	0.01
	Convergent	-3.01	-0.09	-0.41	-0.02

Longitudinal single particle diffusivities, k_{ss}, for Upper Skagit, Northfork cluster and line abreast, and Marsh Channel deployments show that the diffusivity increases for 1016, 396, 665 and 36 seconds, respectively, before k_{ss} values drop off (Fig 4g-i). This drop off in diffusivity values is caused by periodicity in the river shape discussed above. By taking the maxima of k_{ss} as k^{∞}, we can obtain an estimate of the average absolute diffusivity, because of the effects of river periodicity. The time of these maxima corresponds to the decorrelation time of the zero crossing method. In the larger river deployments k_{ss} compares well; estimates are about half that of the relative diffusivity calculation. The Marsh Channel diffusivity differs by an order of magnitude.

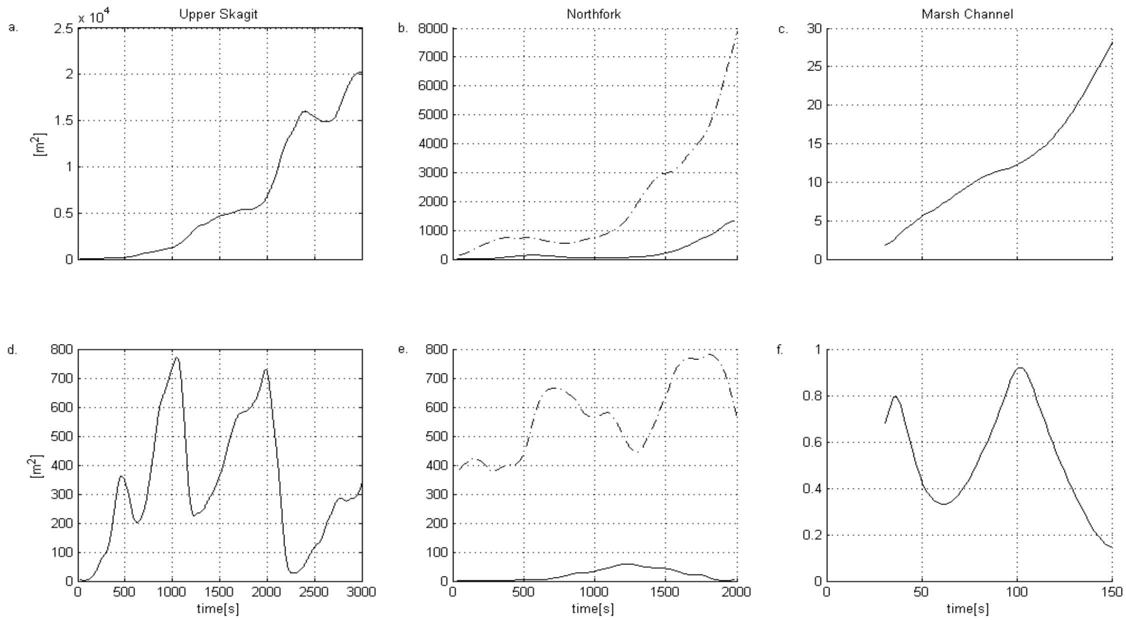

Fig. 6: Longitudinal (a-c) and transverse (d-f) variance of the drifter's positions about the center of mass vs. time for the releases on Upper Skagit (left column), Northfork (middle column) cluster release (solid line) and line abreast release (dashed line) and Marsh Channel (right column). The values of diffusivity are calculated from the slope of a regression line after $t>T_L$.

IV. Discussion – Limitations and Benefits of GPS

Though the use of GPS-equipped drifters in riverine environments has many advantages over traditional Eulerian current observations and dye studies, there are methodological and practical limitations which require consideration. One clear limitation is that drifters only provide surface estimates which may not fully represent tracer dispersion, as dye can mix vertically. Though complete vertical mixing occurs much sooner than transverse mixing, vertical circulations remain important to river kinematics. Surface only observations may result in biased river mixings estimates. Further studies are needed to compare dye and drifter methods in a natural and controlled riverine environment.

The relatively large bin size required for statistical confident mean flow is a limitation, but it is not unique to Lagrangian drifters. Regardless of the measurement method, the largest coherent motions must be observed to ensure statistical confidence. Our results suggest that in rivers with bends increasing the number of drifters or modifying the deployment schemes would not necessarily increase the transverse coverage. Though, carefully paired longitudinal and transverse bin dimensions may provide desired resolutions. For example, the longitudinal bin can be stretched over longer distances which may allow for a higher transverse bin resolution. Additionally, increased spatial coverage can be obtained by multiple releases in specific areas or possibly, but not necessarily, through the use of more drifters. The spatial coverage for flow field mapping cannot be precisely controlled. As shown in Fig 3, drifters may disperse in one section only to converge in another section resulting in a reduction of transverse coverage. Lastly, current handheld GPS-equipped drifters are not ideal for long-term studies because of limited internal battery life (8 hours). Extra batteries can be installed to lengthen the observational time.

V. Conclusion

The application of a new Lagrangian riverine characterization technique fills the observational gaps left by traditional longitudinal tracer methods. Data obtained during an experiment utilizing twenty GPS equipped river drifters provide both Eulerian and Lagrangian observations demonstrating a wide range of riverine applications. Statistical analysis of the high temporal resolution (0.5 Hz) drifter data provides measurements to describe fine-scale riverine processes. Both divergence (positive diffusivity) and convergence (negative diffusivity) is observed in longitudinal and transverse directions. Transverse convergence occurs before the apex in bends, whereas, longitudinal convergence is observed in the exits of bends due to flow deceleration (Fig 3 and 6). River shape induced periodicities in the velocity field are shown in the oscillatory behavior of the autocovariance function. GPS-equipped drifters represent all scales of the surface flow and T_L is directly calculated from the autocovariance function. River studies can be performed at minimal cost and logistical preparation. Prior knowledge or

measurements of a field site are not required. GPS-equipped river drifters are inexpensive, easy to deploy, and provide high temporal and spatial resolution data which provide new insights into river kinematics.

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References

[1] Godfrey, R.G, and Frederick, B.J., 1963. Dispersion in Natural Streams. U.S. Geological Survey Open-File Report, Washington, D.C.
[2] Wilson, J.F., and Forrest, W.E., Potomac River Time-of-Travel Measurements. *Proceedings*, Lamont Geological Observatory Symposium on Diffusion in Oceans and Fresh Waters. Pallisades, N.Y., 1964-1965. pp. 1-18.
[3] Thackston, E.L., and Krenkel, P.A., 1967. Longitudinal Mixing in Natural Streams, 5521, Oct., pp. 67-190.
[4] Fischer, H.B., 1968. Dispersion prediction in natural streams. Journal of Hydraulics Division, ASCE94(5): 927-943.
[5] Godfrey, R.G, and Frederick, B.J., 1970. Stream dispersion at selected sites. U.S. Geological Survey Prof. Paper 433-K, Washington, D.C.
[6] Nordin, C.F., and Sabol, G.V. 1974. Empirical data on longitudinal dispersion in rivers. U.S. Geological Survey Water Resources Investigation, 20-74, Washington, D.C.
[7] Beltaos, S., 1980, Longitudinal Dispersion in rivers, of Hydraulics Division, ASCE 106 No. HY1 pp. 71-83.
[8] Atkinson, T.C. and Davis, P.M., 2000. Longitudinal dispersion in natural channels: 1. Experimental results from the River Severn, *Britian. Hydrol. Earth System Sci*., 4, 345-353.
[9] Ho, D., Schlosser, P., Caplow, T., 2002. Determination of longitudinal dispersion coefficient and net advection in the tidal hudson river with a large-scale, high resolution SF_6 tracer release experiment, *Environ. Sci. Technol*. 2002, 36, 3234-3241.
[10] McQuivey, R.S., and Keefer, T. N., 1974. Simple method for predicting dispersion in streams. *J. Envir. Engrg. Div.,* 100(4), 997 – 1011.
[11] Atkinson, T.C. and Davis, P.M., 2000. Streamwise dispersion in natural channels: 1. Experimental results from the River Severn, *Britian. Hydrol. Earth System Sci*., 4, 345-353.
[12] Boxall, J.B. and Guymer, I., 2006. Streamwise mixing in meandering channels: New experimental data set and verification of a predictive technique. *Water Research,* 41, 341-354.
[13] Davis, R.E., (1985). Drifter observations of coastal surface current during CODE: The method and descriptive view. *J. Geophys. Res*. 90. 4741-4755.
[14] Rutherford J. C. *River Mixing*. Wiley, New York, 1994.
[15] Stockdale, R. J., McLelland, S.J., Middleton, R. and Coulthard, T.J., 2008. Measuring river velocities using GPS river flow tracers (GRiFTers). *Earth Surf. Process. Landforms*, 33, 1315-1322
[16] MacMahan, J., J. Brown, and E.B. Thonton, 2008. Low-cost handheld Global Positioning Systems for measuring surf zone currents. *J. Coastal Res*, DOI: 10.2112/08-1000.1.
[17] Saeki, M. and Hori, M., 2006. Development of an accurate positioning system using low-cost L1 GPS receivers. *Computer-Aided Civil & Infrastructure Engineering,* 21, 258–267.
[18] Legleiter C.J.and Kyriadkidis P.C., 2007. Forward and inverse transformations between Cartesian and channel-fitted coordinate systems for meandering rivers. Mathematical Geology, 38(8), 927-957.
[19] LaCasce, J.H., 2008. Lagrangian statistics from oceanic and atmospheric observations. Lect. Notes Phys. 744, 165-218.
[20] Spydell, M., Fedderssen, F., Guza, R., and Schmidt, W., 2007. Observing surfzone dispersion with drifters. J. Phys. Ocean., 37(12). 2920-2939.
[21] Dever, E., Hendershott, M., and Winant, C., 1998. Statistical aspects of surface drifter observations of circulation in the Santa Barbara Channel, *J. Geophys. Res.*103.24781-24797.